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by

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From recently published information on radon concentrations and on the risk of lung cancer from exposure to radon's decay products, it is estimated that 16,000 lung cancer deaths per year in the United States may be attributed to naturally occurring radon in indoor and outdoor air. Complete implementation of recommendations for limiting indoor radon exposures issued by the U.S. Environmental Protection Agency and Centers for Disease Control (EPA/CDC) would ultimately reduce the radon-attributable lung cancer mortality rate by about 12-22% at an estimated cost (net present value) of $20 billion. Because of the apparent synergistic interaction between radon exposure and cigarette smoking, radon mitigation appears much less cost effective to many individuals than to the society as a whole. With current technology it is also less cost effective to achieve even greater reductions in indoor radon concentrations in the existing housing stock, a national goal recently established by the adoption of an amendment to the Toxic Substances Control Act. We argue that the primary goal of short-term policy should be the identification and reduction of very high indoor concentrations that occur in a small fraction of the housing stock. Substantial reductions in average exposures to radon could be achieved gradually by means of a long-term program with much greater reliability and at much lower expense than is possible with an intensive program.

Exposure to the radioactive decay products of radon is thought to be a leading cause of lung cancer, contributing to the incidence of thousands of cases annually in the United States. The average lifetime risk of lung cancer due to environmental radon exceeds 10^{-3} for individuals in the U.S. population (1). This level of risk is much larger than those ordinarily considered sufficient to warrant intervention by government agencies to limit involuntary exposures to

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environmental contaminants (2). Furthermore, exposures vary over a wide range; indeed, many individuals receive exposures that are at least an order of magnitude larger than the average (3).

Rapidly growing awareness of the indoor radon problem in North America and Europe has generated pressure for governments to take action. In the United States, elements of a national policy have been put forth, such as the recommendations to citizens by the Environmental Protection Agency (EPA) and the Centers for Disease Control (CDC) (4), and the recent adoption of an amendment to the Toxic Substances Control Act (TSCA) (5). Analysis of these elements suggests that, at a minimum, billions of dollars would be required to rapidly and fully implement a national radon-control policy. Because of the large associated costs, it is prudent to examine carefully the implications of policy options. Two aspects of this issue amplify the importance of such an examination: (1) there are no closely related precedents to the problem of indoor radon from which a rational policy may be adapted; and (2) it is likely that federal policies will be needed to address similar indoor air quality issues in the future.

The purpose of this article is to explore federal policy options for controlling indoor radon. We focus on current EPA/CDC policy and on the TSCA amendment, emphasizing the numbers of lung cancers that may be avoided, the costs of implementing control measures, and the prospects for attaining the policy goals. Potential problems in identifying and mitigating high indoor concentrations are considered. Some characteristics that might be expected in a comprehensive policy are presented. First, an overview of the problem is provided as a foundation for subsequent discussion.

TECHNICAL BACKGROUND

Radon Concentrations

Radon-222 is formed by the radioactive decay of ^{226}Ra, a ubiquitous trace element in the earth's crust. With a half-life of 3.8 d, the chemically inert ^{222}Rn atom can migrate a significant distance from its site of generation and enter the atmosphere, either outdoors or within buildings. Radon itself does not pose a substantial health risk; however, it decays to a series of four short-lived, chemically active species (^{218}Po, ^{214}Bi, ^{214}Pb, and ^{214}Po) that can become deposited in the respiratory tract if inhaled. Alpha particles emitted by the decay of the polonium isotopes cause a radiation dose to the cells lining the respiratory tract. Exposure to radon's decay products has been associated with an increased risk of lung cancer in miners and laboratory animals (6, 7).

For most areas of the contiguous United States, the estimated mean outdoor ^{222}Rn concentration is 9 Bq m^{-3} (0.25 pCi l^{-1}) (8, 9). The lowest reported concentrations for outdoor air in the United States are in the vicinity of 1 Bq m^{-3} in Hawaii and Alaska; the highest reported annual average is 28 Bq m^{-3} at Grand Junction, Colorado (9).

Indoor radon concentrations are generally higher than concentrations in nearby outdoor air. A national survey of indoor radon concentrations has not yet been conducted in the United States. However, a mean indoor concentration of approximately 55 Bq m^{-3} for single-family dwellings is suggested both by an analysis of 22 data sets comprising measurements in 817 homes (1) and by the results of year-long monitoring in the homes of 453 physics faculty (10). Significantly, the distribution of indoor radon concentrations across the housing stock is very broad, spanning more than three orders of magnitude. Furthermore, a geographical clustering of high concentrations is observed on a regional scale (1), a fact that may be useful in efficiently identifying homes with high concentrations.

These observations can be understood through an examination of the factors that govern indoor concentrations. For this purpose, a well-mixed, leaky container may be used to represent the building. In steady-state, the indoor radon concentration is given by

$$I = \frac{S_s + S_w + S_b + Q\,I_o}{Q + \lambda V + R} \qquad (1)$$

where I and I_o are, respectively, the indoor and outdoor radon concentration (Bq m^{-3}), Q is the flow rate of outdoor air through the building ($m^3\ s^{-1}$), λ is the radioactive decay rate of radon ($2.1 \times 10^{-6}\ s^{-1}$), R is the effective rate of removing radon from air by means other than ventilation and radioactive decay ($m^3\ s^{-1}$), V is the building volume, and S_s, S_w, and S_b are the entry rates into the building of radon (Bq s^{-1}) from soil, water and building materials, respectively. Generally, $\lambda V << Q$ and $R = 0$, so that $I \sim I_o+(S_s+S_w+S_b)/Q$. By this representation, the indoor concentration is always greater than or equal to the outdoor concentration. Among sources of indoor radon, local soil is the largest. In single-family houses, representative contributions of soil, potable water, and building materials to indoor radon concentrations (S_s/Q, S_w/Q, and S_b/Q) are 55, 2, and 0.4 Bq m^{-3}, respectively (11).

Not only does soil serve as the source of most indoor radon, but geographic variability in the rate of entry from soil is the predominant factor governing the breadth of the distribution of indoor concentrations. Bulk flow of air through soil and/or across building substructure penetrations is driven by mechanically or weather-induced pressure differences. This flow determines, in large part, the rate of radon entry into a building. Other factors that may strongly influence the radon entry rate—soil permeability and radium content—vary broadly over scales ranging from a small fraction of the dimension of a building to hundreds of kilometers. Thus, indoor radon concentrations may differ greatly from one house to another within a neighborhood and the mean concentration may also differ substantially from one region to another. Furthermore, the instantaneous rate of radon entry into any given building may be highly variable, causing indoor radon concentrations to fluctuate markedly. These features pose substantial challenges for the development of an effective radon control strategy, including the identification of homes with concentrations above a remedial-action guideline.

Health Risks

An understanding of the health risks of inhaling radon's decay products is largely based on epidemiological studies of underground miners who were occupationally exposed to elevated concentrations. A recent evaluation of data by a National Research Council committee (BEIR IV) (6) concluded that the best estimate of the average lifetime risk of lung cancer to the general U.S. population from lifetime exposure to radon decay products is 3.5×10^{-4} per working-level-month (WLM) of exposure (12), with the risk for smokers being about an order of magnitude higher than the risk for nonsmokers. This estimate has substantial uncertainty due to a number of factors, some of which cannot readily be quantified. As an indication of the uncertainty, in the past decade, using a common body of epidemiological data, national and international committees have estimated the general population risk to be in the range $(1.3\text{-}7.3) \times 10^{-4}$ per WLM (6).

Although some doubt may remain, it is probable that environmental exposure to radon decay products contributes to the incidence of lung cancer. Inhalation of radon decay products in the absence of other constituents of mining atmospheres has been shown to be carcinogenic for laboratory animals, even with cumulative exposures that are approximately equal to the mean exposure of the U.S. population (6, 13). Furthermore, based on dosimetric calculations, the risk estimates from epidemiological studies of miners are consistent with projections based on the incidence of lung cancer among atomic bomb victims (14). Finally, substantial extrapolation from occupational exposures is not required to obtain risk estimates for the public. A statistically significant excess incidence of lung cancer has been observed among some (but not all) mining cohorts for cumulative exposures down to 35 WLM (6), a factor of two above the estimated mean cumulative exposure for the U.S. public (15), and smaller than the cumulative exposure of some of its members.

The mean rate of exposure of the U.S. public to radon decay products is estimated to be 0.25 WLM y^{-1} (15). Taken in combination with the risk estimates from BEIR IV (6), the estimated current annual mortality rate from lung cancer in the United States attributable to radon exposure is approximately 16,000 cases (16, 17). As shown in Table 1, *only 3% of this mortality rate (about 500 cases) is projected to occur among individuals who have never smoked.* Using the same calculation procedure, we estimate that, if the present U.S. population consisted entirely of life-long nonsmokers, the current annual mortality rate of radon-induced lung cancer would be 1500 cases. Thus, according to these predictions, *more than 90% of the lung-cancer risk* *associated with radon could be controlled by eliminating smoking without any changes in radon concentrations.*

The relative hazard from radon exposure for smokers and nonsmokers, as presented in Table 1, although reflecting the best available information, must be viewed as having large uncertainty. These estimates are based on a model in which the total lung cancer risk is determined by multiplying the risk from radon exposure by the risk in the absence of exposure. Since the baseline risk of lung cancer is much higher for smokers than for nonsmokers, the risk from radon exposure is also much higher for smokers (6). The BEIR IV committee concluded that the available data were incompatible with an additive model, in which the incremental risk from radon exposure would be the same for smokers and nonsmokers. However, the committee also found that "a range of submultiplicative to supramultiplicative models was equally compatible with the data."

From the perspective of public policy, a consideration of *future* rates of radon-associated lung cancer mortality rates is important. Such projections also are highly uncertain because, among other factors, smoking habits are changing substantially with time. For the present paper, estimates were developed by applying the BEIR IV model, with a mean annual exposure of 0.25 WLM, to life tables developed for smoking and nonsmoking males and females (16). As shown in Table 1, the predicted radon-associated lung cancer mortality rate for this population is about the same as the predicted rates for the current population. Only 7% of radon-associated lung cancers are predicted to occur among nonsmokers in the stable population.

Mitigation Measures

Control measures can be applied to reduce high indoor radon concentrations using two basic approaches: (1) reduce the rate at which radon enters from its sources or (2) increase the rate of removal of radon from indoor air, for example by increasing the ventilation rate. If additional ventilation is to be used, energy-recovery devices can be incorporated to reduce the operating cost (18). Because of the large site-to-site variability of the radon entry rate from soil relative to the more moderate variability in ventilation rate, the most effective control methods often are those that prevent the entry of soil gas through building substructures. Sealing pathways of soil gas entry can be effective by itself, but only if the leaks are completely eliminated and maintained so (19). A more effective approach is to mechanically ventilate the soil near the substructure (20). This method works by a combination of (1) reversing the direction of air flow across the substructure penetrations and (2) diluting the radon concentration in the soil adjacent to substructure. A third method is to pressurize the building substructure, again causing air to exit the building rather than enter through substructure penetrations.

Alternative techniques can be employed for those cases in which potable water (21) or building materials (22) are dominant sources.

From the available evidence, elevated radon concentrations in most residences can be reduced to below 150 Bq m^{-3} (4 pCi l^{-1}) by practical application of one or more of these techniques (20). Long-term effectiveness of these methods is essential to maintain reduced risks. Case studies have demonstrated a significant failure rate of mitigation measures within a few years following installation (23). Consequently, follow-up monitoring and corrective action must be a part of any control program.

IMPLICATIONS OF CURRENT U.S. POLICY FOR CONTROLLING RADON EXPOSURES

Two elements constitute the core of present United States federal policy for controlling exposures to indoor radon. First, the U.S. Environmental Protection Agency (EPA) and the Centers for Disease Control (CDC) have made recommendations and provided guidance to citizens that include a measurement protocol and guidelines for taking remedial action to limit radon levels in their homes (4, 25). Second, an amendment to the Toxic Substances Control Act has recently been adopted that, among other provisions, establishes a long-term national goal of greatly reducing indoor radon concentrations (5). In this section, these policy elements are described, and the cost and reductions in risk associated with successful implementation of the policies are discussed (24).

Recommendations to Citizens

The EPA and CDC have recommended that a screening measurement for indoor radon concentration be made in every household located below a building's third story above ground (25). The measurement protocol calls for a two-day average sample to be taken, under closed-house conditions, on the lowest livable level of the home (4). If the measurement result is above 4 pCi l^{-1} (150 Bq m^{-3}), follow-up measurements are recommended to better determine the average concentration to which occupants are exposed. If the follow-up measurements yield an average result in excess of 4 pCi l^{-1}, it is recommended that corrective action be taken to permanently reduce indoor concentrations. Recommendations on the duration of follow-up measurements and the urgency for corrective action depend on the results of the indoor concentration measurement. The rationale for setting the principal criterion at 4 pCi l^{-1} combines historical precedent and the objective of reducing exposures to the extent judged reasonable, given that no exposure can be considered risk-free.

It is important to note that these recommendations do not constitute standards. According to the present philosophy, it is to be left to individual residents to weigh the risks of radon exposure against the costs of control. In this regard, the strategy for controlling indoor radon departs radically from that for controlling outdoor air pollutants. In the latter case, federal standards have been established, control measures have been implemented, and the imposition of sanctions has been threatened for regions that do not achieve compliance. The differences in approach arise naturally because outdoor air is a community resource, whereas indoor environments are largely private (26). However, this position does not accommodate the public resource aspects of the building stock, as discussed in a later section.

The estimated cost of implementing the EPA/CDC recommendations in the current housing stock is approximately $2.2 billion for measurement and $6.6 billion for remediation plus $0.8 billion per year for operation and maintenance (27). Using an annual discount rate of 5% with a 30-year time horizon, the net present value of the costs for measurement and remediation is $20 billion.

The benefit in reducing risks depends on the average effectiveness of remediation. If all single-family dwellings having a radon concentration above 150 Bq m^{-3} (4 pCi l^{-1}) were reduced to the present average of 55 Bq m^{-3}, the reduction in total population exposure would be 22% (28). If the mitigation measures were less effective, so that the average concentration in remediated housing were 150 Bq m^{-3}, the reduction in total population exposure would be 12%. The mean of these two results, i.e. reduction to an average of 100 Bq m^{-3}, is used here for illustration. According to the risk estimates presented in Table 1 for a stable population, *complete implementation of the current EPA/CDC policy would reduce the population exposure by 17%, ultimately leading to an annual avoidance of 2700 lung cancer mortalities per year (2500 among smokers and 200 among nonsmokers).* An annual lung cancer mortality rate of 13,000 cases would still be attributed to radon exposures.

Assuming a 30-year average effective lifetime for remediated households, the average cost (net present value) per lung cancer death averted under the current guidelines is estimated to be $0.25 million (29). This compares favorably with the range of $0.4-7 million per death averted that the EPA considers reasonable to justify the cost of controlling an environmental pollutant (30). However, the case of indoor radon is not analogous to the situations in which an activity by some external organization is responsible for the hazardous exposure, and public funds are to be spent for remediation. By alternative analogies, radon remediation is not as attractive. For example, the costs per death averted for installing smoke detectors in homes and for installing passive restraints in automobiles have been estimated at $30,000 and $100,000, respectively, and yet these risk-reducing measures are not uniformly required (31).

As the guideline for remedial action increases, the average cost-effectiveness of radon control improves. Table 2 shows the results for five action levels applied to single-family dwellings, assuming in each case that remedial measures reduce the average indoor concentration to 100 Bq m^{-3}, and that the average cost of remediation is independent of the action level. These action levels correspond approximately to the range of values recommended in different countries (31). At the higher guideline levels, most of the cost is associated with the screening measurement program. Mitigation at these higher levels could be made much more cost effective by developing efficient means for identifying households with elevated concentrations, e.g., by first identifying areas with high average concentrations, then monitoring intensively in those areas.

For this range of action guidelines, the reduction in population exposure resulting from a successful mitigation program is a small fraction, 0.01-0.17, of the current exposure. To reduce the current population exposure by a large fraction, remediation would be required in a majority of households, with an action guideline much lower than the current EPA/CDC recommendation. For an action level below 150 Bq m^{-3} (4 pCi l^{-1}), the cost-effectiveness of mitigation is uncertain, but would probably be reduced. A larger fraction of households would require remediation, reducing the average cost per home of identifying those above the criterion. However, most of the cost would be associated with mitigation, and the cost of remediation per household may be higher. Furthermore, the average reduction in exposure per home remediated would be smaller. At present there is little practical experience with reducing indoor radon to a concentration below 150 Bq m^{-3}.

Because of the apparent synergistic interaction between smoking and radon, and because of the mobility of the U.S. population, the cost of controlling indoor radon is less attractive to certain individuals than to society as a whole. Consider, for example, an owner-occupied residence inhabited by four lifelong nonsmokers: two adults, aged 40 (male and female), and two children, aged 10 (male and female). Assume that the home is to be occupied for ten years before the family moves, that the mean indoor radon concentration is 260 Bq m^{-3} (the mean concentration in households with a concentration above 150 Bq m^{-3} according to the lognormal representation of the distribution from ref. 1), and that remediation at the mean cost cited earlier would reduce the mean indoor concentration to 100 Bq m^{-3}. The average net present value of the homeowner's cost for remediation would be approximately $3000 (32). The remediation would lead to a cumulative reduction in exposure per household of 33 WLM for the four occupants over ten years (33). From the risk projections of the BEIR IV committee, the lifetime risk of one lung cancer death in the family would be 0.0232 in the absence of remediation and 0.0220 with remediation. The informed homeowner would be faced with this question: *Is it worthwhile to spend $3000 today to reduce the risk by about 5% in relative terms (or about 1 in 800 in absolute terms) that someone in my family will die of lung cancer ?* For a cohort of such households, an average of one lung cancer death would be avoided for every 800 homes remediated. Thus, the average cost (net present value) per lung cancer death averted is $2.4 million, not including the expense of initially identifying the households. Since the costs of remediation are not strongly dependent on the initial radon concentration, applying control becomes progressively more attractive at higher indoor concentrations, but progressively less so at lower concentrations. Also, the initial expense of installing a radon-mitigation system may be recovered when the home is sold, thereby reducing the overall mitigation cost to the present homeowner.

From the perspective of a household in which there are smokers, the cost of radon remediation appears more attractive. If, in the previous example, all four family members were—or, in the case of the children, would become—smokers, the lifetime risk of at least one lung cancer death in the family would be 0.36 without remediation and would be reduced by 0.017 (to 0.34) with radon mitigation. The reduction in absolute risk is more than an order of magnitude larger than for the nonsmoking family at the same cost. On average, one lung-cancer death would be averted in a cohort of 60 such households in which mitigation was applied, implying an average cost per lung cancer death averted of only $180,000 (again excluding the cost of initially identifying the houses). However, in the absence of incentives such as low-interest loans for remediation, it seems unlikely that most smokers would make the necessary investment to reduce the radon-related risk of lung cancer when the dominant cause of their risk is smoking.

From a public health perspective, the goal of reducing lung cancer incidence also may be more easily met by changing the population's smoking habits rather than by aggressive measures to reduce indoor radon concentrations. The large majority of the annual lung cancer death rate of 130,000 cases in the United States is attributed to cigarette smoking (34). *A permanent reduction by about 3% in the number of cigarette smokers would reduce the annual mortality due to lung cancer by the same amount as a radon-mitigation program that succeeded in achieving the EPA/CDC recommendations*. The overall health benefit from reducing smoking to this extent would be much larger, since lung cancer is only one of several diseases to which smoking contributes.

Toxic Substances Control Act Amendment

By legislation, a long-term national goal was recently established to make air within buildings in the United States "as free of radon as the ambient air outside of buildings" (5). The legislation contains several provisions to promote movement towards this goal, such as a requirement that EPA develop model construction standards for new buildings.

The implications of measures needed to achieve this goal are staggering. From equation (1) the indoor radon concentration can only be reduced to the outdoor level by greatly reducing radon entry from soil, potable water, *and* building materials. As it is unlikely that radon entry from these sources could be completely prevented, it would also be necessary to remove radon from indoor air by filtration, for example with activated carbon (35). Whether this goal could be achieved in the existing housing stock is unclear. Certainly, substantial improvements in radon measurement and mitigation technology would be required. Even if it is technically feasible, the costs would be prohibitively large, on the order of $1 trillion (36).

If this long-term national goal were achieved, the average cumulative exposure of the U.S. population to radon decay products would be lowered by about 75% (37), reducing the annual mortality from radon-related lung cancers by about 12,000 cases per year (11,100 cases averted per year among smokers, 800 among nonsmokers). An annual incidence of 4,000 lung cancer deaths still would be attributed to radon exposure. Again assuming a 30-year effectiveness of mitigation, the cost per lung cancer averted is estimated to be about $5 million.

Because mitigation measures cost less to apply in new construction than in remediation, this objective would be less impractical, but still difficult and costly to achieve, if it were implemented gradually in new housing. Even in this case, though, an annual investment of at least several billion dollars might be required (38).

PITFALLS AND OTHER PROBLEMS

For the analyses of the previous section it was assumed that current technology for radon measurement and mitigation would be applied effectively. In fact, a number of problems may prevent policy objectives from being achieved efficiently, as discussed in this section.

Limitations of Measurement and Mitigation Technology

Most of the mitigation experience in the United States has been developed over the past few years in New York, New Jersey, Pennsylvania, and Washington. This experience is too recent to yield reliable information on the long-term efficacy of remedial measures, a necessary feature of an effective control program. Studies conducted a few years after installation indicate that a monitoring and maintenance program is necessary to ensure that mitigation measures continue to function effectively (23). Moreover, building practices vary widely across the country, so that the experience gained in one region may not be directly transferrable to another.

Quality assurance in radon detection is promoted by a measurement proficiency program established by the Environmental Protection Agency (39). This program is necessary; however, it is not clear that it is sufficient to ensure accurate measurements at concentrations near the guideline. In the test protocol, several detectors are exposed to an elevated, constant concentration of radon in a controlled atmosphere. By contrast, in measuring indoor concentrations, one or two detectors are exposed to a varying concentration of radon, which is often much lower than that used in the test protocol, in an atmosphere in which temperature and humidity may be uncontrolled. Moreover, "blind" tests—i.e., those in which the vendors do not know that their detectors are being tested—are only now being incorporated into the program. As a result, the true measurement uncertainty for a single measurement in a residence may be larger than suggested by the 25% criterion for passing the test.

To achieve the long-term national goal, substantial improvements in measurement and mitigation technology would be required. Inexpensive monitoring devices routinely used for screening and longer-term integrated measurements are not sufficiently sensitive to measure outdoor radon concentrations accurately (a necessity for determining that the goal is being met). Equally important, there has been no direct experimental demonstration that indoor concentrations of radon can be practically reduced to outdoor levels.

Misuse of Screening Measurement Results

Under current practice, one can expect many houses to be misclassified with respect to the 4 pCi l^{-1} (150 Bq m^{-3}) guideline. The EPA protocol entails a two-day screening measurement, under closed-house conditions, on the lowest livable level of the home. The intention is to produce the highest indoor concentration that may be sustained in the home. The screening measurement permits rapid action for those homes in which the indoor radon concentration is exceedingly high. However, indoor radon concentrations fluctuate markedly, even under closed-house conditions, and the fluctuation periods can exceed the two-day screening measurement period (40). One cannot conclude from a single screening measurement result below 150 Bq m^{-3} that the annual average result for the household is below the guideline.

The results of screening measurements have also been misinterpreted in projecting the magnitude of the radon problem in U.S. housing. Surveys have been conducted using the screening protocol in seventeen states over the past few years. A significant fraction of the households in each state yielded measurements exceeding 150 Bq m^{-3}, a fact that was used to substantiate the recommendation for screening measurements in most homes. It is recognized by many that these results overstate the size of the problem because the measurements were made in closed houses and often in basements where concentrations are elevated (41). It is less well understood that an overestimate of the fraction of homes exceeding 150 Bq m^{-3} also would result from the two-day measurement protocol even if the measurements were conducted under ordinary living conditions (42).

Public Resources vs. Private Choice

The objectives of current EPA/CDC policy cannot be met without widespread public compliance. The extent to which the U.S. public will follow these recommendations is not known. However, experience in New Jersey suggests that even with a highly publicized and large local radon problem, and despite substantial support and encouragement from governmental agencies, only a small fraction of residents have had a measurement made of the radon concentration in their home (43). Furthermore, much of the measurement and mitigation effort has occurred with real estate transfers, suggesting that economic concerns about radon exceed personal health concerns.

To an extent, the decisions about whether to measure and to mitigate are appropriately left to individual residents. However, there is a public interest in reducing indoor radon exposures. Because the U.S. population is highly mobile, a homeowner will be less likely to adopt control measures than would the society operating as a unit unless mitigation is required or unless its cost is recovered through increased property values. Furthermore, the costs of medical care are largely borne by society through insurance, rather than directly by individuals. In addition, under the current policy, remediation is unlikely in homes that are rented.

Unobservable Consequences

Although the projected health consequences associated with indoor radon exposure are large, it has not yet been possible and will be difficult in the future to demonstrate a compelling association between environmental radon exposure and lung cancer rates. Also, because of the separation in time between exposure and effect, and because of the large incidence of lung cancer from smoking, a specific lung cancer death cannot reliably be attributed to radon exposure. Amidst this uncertainty, arguments are put forth that indoor exposures to radon are much less hazardous than the risk projections presented in this paper would suggest (44). Such controversy diminishes the will of the public to take corrective action.

In addition, it is important to recognize that even with an aggressive program to reduce radon exposures, benefits will not be observed quickly. There is a latency period following exposure before the onset of illness. Thus, following a change in the population exposure, no change in lung cancer rate would be expected until the latency period (five years, according to the BEIR IV committee (6)) has elapsed. Evidence also suggests that increased risk due to exposure persists (with some reduction in magnitude) throughout life. Therefore, decades would elapse following full implementation of remediation measures before a substantial fraction of the benefit of reduced risks would be expressed, and even then the reduced risks may not be detectable, particularly if cigarette smoking habits continue to change.

Homes with Extremely High Concentrations

According to the parameters of the lognormal distribution of indoor radon concentrations presented in Ref. 1, there are approximately 70,000 homes in the United States in which the average radon concentration exceeds 800 Bq m^{-3}. At this level, a 75%-time occupant receives a cumulative exposure of 4 WLM y^{-1}, equal to the limit for underground uranium miners (45). For an individual exposed at this level throughout life, the risk of lung cancer is extraordinarily high, ranging from 3% for female nonsmokers to 40% for male smokers (6, 46). By almost any criterion, this level of health risk due to involuntary exposure to radon's decay products in one's home is unacceptable. It should be a high priority to rapidly identify these homes and take corrective measures to reduce exposures in them. The establishment of the stringent long-term national goal may divert attention and resources from those homes in which the problem is acute. Indeed, strict emphasis on achieving the EPA guideline in the millions of homes that have concentrations only moderately above 150 Bq m^{-3} may dilute the overall effectiveness of the effort to identify and take remedial action in the small fraction of these homes in which the indoor radon concentration is extraordinarily large.

MOVING TOWARDS A COHERENT POLICY

In this section, some important characteristics of a reasoned response to indoor radon are discussed. These issues are, at best, underemphasized in the current approach. In our view, these aspects must be explicitly incorporated to make effective progress toward the goal of reducing indoor radon exposures.

Systematically Develop a Control Strategy

A comprehensive control strategy for limiting exposure to indoor radon may be viewed as having three key elements (31). Exposure guidelines, based on health effects data and costs of control, constitute the first element. The second element is the identification or classification of buildings with respect to their potential to contribute to exposures which exceed these guidelines. This element includes development of measurement methods and the interpretation of the data obtained. The third element is control, incorporating both the specific techniques for reducing concentrations and the methods for choosing appropriate techniques for a given situation.

Each of these elements can be found in present federal policy. Much of this article addresses opportunities to improve performance on specific aspects of these elements. However, formulating these elements independently does not, by itself, constitute the development of a comprehensive strategy. Effort must also be devoted to resolving some fundamental, underlying issues in controlling radon and other indoor air pollutants as well. For example, the respective responsibilities of the concerned parties—owners, occupants, builders, and local, state, and federal governments—remain ambiguous. A cohesive strategy for controlling indoor radon cannot be developed without integrating technical assessments with an understanding of political, economic, and legal aspects of the issue. Beyond establishing objectives, methods for achieving these goals must be carefully planned. To do so requires a concerted, explicit effort.

Use All Available Information to Identify Buildings with Elevated Concentrations

The EPA/CDC recommendation that a screening measurement be made in virtually every home is an inefficient means to achieve the goal of identifying homes with annual average concentrations exceeding 150 Bq m^{-3} (4 pCi l^{-1}). The major value of a screening measurement is to identify homes in which the radon concentrations are so high that remedial action should be taken before an annual or seasonal average measurement can be completed. (Even in homes with concentrations above 200 pCi l^{-1} (7400 Bq m^{-3}), it is recommended that a follow-up short-term (one-week) measurement be made before undertaking remedial measures.) These homes constitute a very small fraction of the housing stock, and, because they occur in clusters, can be identified more efficiently by methods other than measuring every household. Increased attention should be given to the possibility of using geological information, in combination with radon concentration measurements in a sample of homes in a region, to identify areas in which a significant probability of very high concentrations exists (47). Greater effort should also be devoted to developing mechanisms for providing information to residents on the distribution of indoor radon concentrations in their communities so they can make informed decisions on whether to measure radon in their homes (43).

Increase Emphasis on Long-Term Measurements made under Normal Living Conditions

Because of the large, naturally occurring, temporal variations in indoor radon concentrations, screening measurements cannot be considered a reliable indicator of long-term average exposure conditions, the parameter of concern for assessing the risk of lung cancer. Misinterpretation of the results of screening measurements has generated much confusion about the extent of the indoor radon problem. Instead of encouraging screening measurements, measurements of long-term average concentrations under actual living conditions should be promoted. The results of these measurements provide a superior basis for making decisions about remediation.

Foster a Public Consensus

To a greater extent than for the control of many other environmental pollutants, public support and cooperation are vital for achieving reductions in radon exposure. Public information and training provided by the EPA contribute to this goal, but more could be done. For example, EPA's establishment of a remedial action guideline may yield a *de facto* standard that affects much of the population without any formal mechanism for criteria development, scientific review, or public comment (48). The federal government's response to indoor radon should be reassessed through a means that encourages discussion and debate.

Establish a Realistic Long-Term Goal

Much of the cost to achieve the long-term national goal established by the TSCA amendment would be spent to achieve small marginal reductions in exposure. Most of the benefit of this goal could be realized at a small fraction of the cost by establishing a target concentration in the vicinity of 25-50 Bq m^{-3} and by attempting to achieve this goal only in new construction. The long-term goal should be supported by a plan for attainment, including a time frame.

Nurture a Steady Response

Wherever possible, federal policy should promote a steady development of radon measurement and mitigation expertise, rather than a boom-bust cycle. Indoor radon is a widespread problem and there is a long history of human exposures. A crash program to identify and mitigate homes above the present guideline is inefficient. If a backlash of public opinion were to result from, for example, an overstatement of the magnitude of the problem, then the ultimate benefit may be smaller than that which could be achieved by a more efficient, gradual response. Steady development would permit the growth of an infrastructure of trained individuals and businesses. Mitigation measures could be steadily improved. Better measurement techniques might be developed. More information would become available on the health risks of environmental exposures, yielding a stronger basis for mitigation decisions. These benefits cannot be realized if the radon problem is treated as an epidemic that requires rapid countermeasures with little regard for scientific uncertainties and accompanying costs.

A steady response will be encouraged if our primary short-term goal is to identify and apply remedial measures in houses having indoor concentrations that are extremely high. By reducing radon concentrations in these homes, we can ensure that individual risks due to indoor radon exposure are not extraordinarily high relative to those that are routinely accepted in association with other activities, such as riding in a car. With vigorous and focused effort, it might be possible to identify and correct excessive concentrations in these homes within a few years. Ultimately, any substantial reduction in the cumulative population exposure would require concentration reductions in a large fraction of the building stock. If this goal is to be sought, it could best be accomplished gradually, with relatively stringent controls applied to new construction and, possibly, a second level of control in existing buildings. As decades would be required to achieve such a goal, the opportunity is available to deliberately consider its merits and costs, and to improve the basis for making decisions by developing additional information. We are most likely to reduce radon-related health risks at reasonable cost only if we apply a sustained and steady effort to the problem of reducing indoor exposures.

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2. For example, see W. L. Lappenbusch and C. R. Cothern, *Health Phys.* 48, 535 (1985).
3. A lognormal distribution with parameters determined by Nero et al. (ref. 1) suggests 0.4% of 60 million single-family houses have concentrations at least 10 times the mean.

4. United States Environmental Protection Agency and U.S. Department of Health and Human Services, *A Citizen's Guide to Radon: What It Is and What To Do About It* (OPA-86-004, U.S. Government Printing Office, Washington, DC, 1986); M. Ronca-Battista, P. Magno, and P. C. Nyberg, *Health Phys.* **55**, 67 (1988).

5. Indoor Radon Abatement Act of 1988, Title III of the Toxic Substances Control Act, PL 100-551.

6. Committee on the Biological Effects of Ionizing Radiations, *Health Risks of Radon and Other Internally Deposited Alpha Emitters: BEIR IV* (National Academy Press, Washington, DC, 1988).

7. The risks associated with exposure to the decay products of a second radon isotope (^{220}Rn) may also be substantial, although smaller than those due to ^{222}Rn, because of the shorter half-life of ^{220}Rn (56 s). A third radon isotope (^{219}Rn) is not thought to pose a substantial risk because of its even shorter half-life (4 s), and because the natural abundance of elements in its decay chain (headed by ^{235}U) is a hundred times smaller than the abundance of the ^{222}Rn chain (headed by ^{238}U) and of the ^{220}Rn chain (headed by ^{232}Th).

8. The SI unit for activity concentration, Bq m^{-3}, is equivalent to 0.027 pCi l^{-1}, the traditional unit.

9. T. F. Gesell, *Health Phys.* **45**, 289 (1983).

10. B. L. Cohen, *ibid.* **51**, 175 (1986).

11. A. V. Nero, in *Radon and Its Decay Products in Indoor Air*, W. W. Nazaroff and A. V. Nero, Eds. (Wiley, New York, 1988) Table 1.3.

12. One working level month (WLM) is defined as an exposure to the short-lived radon decay products equivalent to 173 hours (a working month) at a potential alpha energy concentration of 1 WL = 2.08×10^{-5} J m^{-3}. Under typical indoor conditions, 7400 Bq m^{-3} (200 pCi l^{-1}) of ^{222}Rn yields one WL.

13. F. T. Cross, in *Radon and Its Decay Products in Indoor Air*, W. W. Nazaroff and A. V. Nero, Eds. (Wiley, New York, 1988), p. 373-404.

14. A. C. James, *ibid.*, p. 259-309.

15. A. V. Nero, *Atmos. Environ.* **22**, 2205 (1988).

16. For the current population, data were obtained from the following sources: (a) total population by age and sex from 1986 deaths and death rates, U. S. Department of Health and Human Services, *Monthly Vital Statistics Report* **37(6)**, supplement (1988); (b) population smoking habits by age and sex from U.S. Bureau of the Census, *Statistical Abstract of the United States: 1988* (108th edition, Washington, DC, 1987) Table 182; (c) relative risks of death due to lung cancer by age, sex, and smoking habit from M. E. Mattson, E. S. Pollack, J. W. Cullen, *Amer. J. Public Health* **77**, 425 (1987); (d) total lung cancer mortality rates by age and sex from National Center for Health Statistics, *Vital Statistics of the United States, 1986* (DHHS Pub. No. (PHS) 88-1114, U.S. Government Printing Office, Washington, DC,

1988) Table 8.5. For the stable population calculations, individuals were assumed to either begin a lifelong smoking habit at age 20 or to never smoke. The proportion of males and females at 20 who smoke was taken to be 0.44 and 0.45, respectively, corresponding to the respective proportions in the age group 20-24 who have ever smoked (reference cited in b above). Separate life tables were constructed by sex and smoking status using 1986 mortality statistics (reference cited in a above) and relative mortality rates by all causes for light smokers (less than 25 cigarettes per day) and persons who have never smoked (reference cited in c above). Lung cancer death rates were assumed to be the same as for the current population. For both conditions, lung cancer mortality rates were corrected for radon-attributable lung cancer incidence to obtain non-exposed incidence rates.

17. An estimate of 14,300 lung cancer deaths per year attributable to radon is obtained from a different application of the BEIR IV model using the data of Nero et al. (ref. 1) by J. H. Lubin and J. D. Boice, Jr., *Health Phys*. (submitted for publication). The 10% difference between the two estimates arises from several factors including different assumptions about the prevalence of smoking and the relative risk of lung cancer for smokers vs. nonsmokers. In addition, the estimate of Lubin and Boice does not include the contribution of irreducible exposures (i.e., natural background exposures), considered by them to be 0.015 WLM y^{-1}, or 6% of the average exposure.

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22. E. Stranden in *Radon and Its Decay Products in Indoor Air*, W. W. Nazaroff and A. V. Nero, Eds. (Wiley, New York, 1988) pp. 113-130.

23. R. J. Prill, W. J. Fisk, and B. H. Turk, *Monitoring and Evaluation of Radon Mitigation Systems over a Two-Year Period* (LBL-25909, Lawrence Berkeley Laboratory, Berkeley,

1988); I. A. Nitschke, M. E. Clarkin, T. Brennan, J. E. Rizzuto, and M. Osborne, *Long-Term Assessment of Residential Radon-Mitigation Systems*, (paper 88-107.5, Air Pollution Control Association, Pittsburgh, PA, 1988).

24. The Office of Drinking Water of the U.S. EPA is planning to propose a standard to limit radon in public water supplies because of the health risk posed by inhalation of decay products following radon release from the indoor use of water: *Federal Register* **51**, 34836 (30 September 1986). The costs and potential risk reductions are much smaller than those associated with the EPA/CDC recommendations and TSCA amendment considered in this paper.

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27. Screening measurements would be required in approximately 80 million residences at a unit cost of $15 for a charcoal monitor. Based on the EPA reports that 20-30% of homes exceed the 150 Bq m^{-3} (4 pCi l^{-1}) criterion in screening measurements, subsequent monitoring would be required in approximately 20 million residences at a unit cost of $50 for two alpha-track monitors capable of measuring long-term average concentrations. Mitigation would be required in 7.3% of 60 million single-family dwellings at an estimated mean cost of $1500 for installation, corresponding to the median cost of installing a subslab ventilation system (B. H. Turk, R. J. Prill, W. J. Fisk, D. T. Grimsrud, and R. G. Sextro, *J. Air Pollut. Contr. Assoc.*, submitted for publication). Annual operation and maintenance costs are estimated as $185 per remediated household, broken down as follows: $100 for electricity to operate the fan (1300 kWh at $0.075/kWh), $35 for gas-fired space heating to compensate for additional air exchange (0.2 air changes per hour in a 300 m^3 home located in a 2800 degree-day (centigrade, base 18 C) climate, at $0.57/therm), and $50 for annual monitoring, occasional fan replacement, and additional minor maintenance. The cost data apply for homes with basements; less information is available on the cost of reducing radon levels in houses with slab-on-grade or crawl-space substructures.

28. Radon concentrations would be reduced from an average of 260 Bq m^{-3} to 55 Bq m^{-3} in 4.4 million dwellings (7.3% of the 60 million single-family residences), housing 12 million individuals. Assuming average occupancy of 75%, and 50% equilibrium between radon's decay products and radon, the exposure rate would be reduced by an average of 1.07 WLM y^{-1} for these 12 million individuals, corresponding to 0.054 WLM y^{-1} or 22% when averaged over the entire population.

29. Cost (net present value) per death averted computed as $20 billion/(30 years × 2700 cases y^{-1}) = $0.25 million per case.

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32. Installation cost of $1500, plus $185 per year in operation and maintenance expenses, discounted at an annual rate of 5%. See Ref. 27.

33. Reduction by 160 Bq m^{-3} corresponds to 0.84 WLM y^{-1} $person^{-1}$ in avoided exposure assuming 75% occupancy and 50% equilibrium between radon's decay products and radon.

34. National Center for Health Statistics, *Vital Statistics of the United States, 1986* (DHHS Pub. No. (PHS) 88-1114, U.S. Government Printing Office, Washington, DC, 1988) Table 8.5; it is estimated that 85% of lung cancer deaths could have been avoided if the individuals had never smoked, U.S. Department of Health and Human Services, *The Health Consequences of Smoking: Cancer* (U.S. Government Printing Office, Washington, DC, 1982).

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36. Only a rough estimate is possible, since there is no experience with reducing radon to this extent. The average net present value of the initial and operating cost per household remediated is estimated to be in the range $10,000-$16,000. Mitigation steps (and approximate average costs) are these: (a) reduce soil gas entry to meet current EPA guideline, $3-5 K; (b) further reduce soil gas entry to near zero ($3-5 K); (c) use activated charcoal or alternative filtration technique to remove radon from indoor air ($4-6 K); (d) limit radon concentration in potable water supplies (small); and (e) limit radon from building materials (small). These measures would have to be applied in most of the 90 million U.S. residences to achieve the long-term national goal. If applied in 70 million households, the total net present value of the cost would be on the order of $1 trillion.

37. Continuous exposure to the average outdoor level of 9 Bq m^{-3} results in an estimated cumulative exposure to radon decay products of 0.063 WLM y^{-1}, or 25% of the estimated current exposure, 0.25 WLM y^{-1}.

38. Cost per household of several thousand dollars for each of one million new housing units constructed annually.

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42. Because of the large temporal fluctuations in concentrations, some homes with annual averages below 150 Bq m^{-3} will be measured at greater than 150 Bq m^{-3}, and, conversely, some homes with annual averages above 150 Bq m^{-3} will be measured at concentrations below this guideline. But, because of the shape of the distribution of indoor concentrations, among all homes with mean concentrations within an increment, ε, of the 150 Bq m^{-3} guideline, many more are below rather than above this level. Therefore, the incidence of false positives is expected to exceed the incidence of false negatives, and so the number of homes above the guideline is overestimated.

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49. We thank several colleagues for their comments on this paper: J. Daisey, W. Fisk, J. Girman, D. Grimsrud, A. Nero, S. Rose, R. Sextro, and J. Wesolowski. This work was supported in part by the Director, Office of Energy Research, Office of Health and Environmental Research, Human Health and Assessments Division and Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Table 1. Estimated annual lung cancer deaths in the United States attributable to radon exposure (1, 6, 16). *

	Population 1000s	Lung Cancer Death Rate (y^{-1}) All Causes	Radon-Attributable
Current Population (1986)			
Male			
never smoked	63,900	1,900	200
former smoker	26,100	42,900	4,800
current, light smoker +	18,200	21,400	2,600
current, heavy smoker +	8,900	22,600	3,100
Female			
never smoked	81,300	3,100	300
former smoker	17,100	14,700	1,700
current, light smoker +	20,000	15,800	1,900
current, heavy smoker +	5,300	8,000	1,100
Male, total	117,400	88,800	10,700
Female, total	123,700	41,600	5,000
Current population, total	241,100	130,400	15,700
Stable Population			
Male			
nonsmoker	80,500	6,000	700
smoker	36,800	75,000	8,500
Female			
nonsmoker	82,800	4,000	450
smoker	40,900	57,000	6,300
Male, total	117,400	81,000	9,100
Female, total	123,700	61,000	6,800
Stable population, total	241,100	142,000	15,900

* Individual entries rounded. + Light smoker defined as one smoking less than 25 cigarettes per day.

Table 2. Societal costs and health benefits associated with different action limits for indoor radon control *

Guideline ($Bq\ m^{-3}$)	Guideline (pCi/l)	Affected Homes million	Pop. Exp. Reduction %	Deaths Averted No./30 years	Aggregate Cost (NPV, $billion) Meas.	Aggregate Cost (NPV, $billion) Mitigat.	Aggregate Cost (NPV, $billion) Total	Cost per Death Averted (NPV, $thousand)
150	4	4.2	17	81,000	2.0	18	20	250
250	7	1.4	10	48,000	1.5	6.1	7.6	160
400	11	0.4	5	24,000	1.3	1.7	3.0	125
600	16	0.1	2	9,000	1.2	0.4	1.6	180
800	22	0.04	1	4,800	1.2	0.2	1.4	290

* Assumptions: (a) only single family dwellings exceed guideline; (b) reduction to 100 $Bq\ m^{-3}$ achieved in each remediation; (c) distribution of radon concentration in single-family dwellings as given in reference 1; (d) dose reduction averaged over entire population, assuming average exposure equals 0.25 WLM/y; (e) 69% of population lives in 60 million single family residences with an average occupancy of 75%; (f) premature lung cancer deaths averted computed assuming the mitigation measures are effective over a thirty year period; (g) cost data: screening measurement @ $15 each in 80 million residential dwellings, follow-up measurement @ $50 in four times the number of homes requiring mitigation, and net present value of installation ($1500), operation ($135 per year) and maintenance ($50 per year) of mitigation system is $4340, computed with a 5% discount rate.